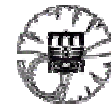# Elliptic flow and HBT radii from a relativistic hydrodynamic model with early chemical freeze out

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Contents:
- Introduction & motivation
- EOS of chemically equilibrium & non-equilibrium hadronic matter
- Hydrodynamic simulations
- p_t spectra, v_2 & HBT radii
- Summary & discussion

Talk based on
- T. Hirano and K. Tsuda, nucl-th/0205043.
- T. Hirano and K. Tsuda, nucl-th/0202033.

See also,
- T. Hirano, PRC**65**, 011901 (2002).
- T. Hirano, PRL**86**, 2754 (2001).

Full 3D Hydro in the τ-η_s Coordinate[*]

➢No cylindrical symmetry

   ➔ Enables us to simulate non-central collisions.

      ➔➔ Elliptic flow, HBT radii in $b \neq 0$ collisions

➢No Bjorken's scaling ansatz $(Y_f \neq \eta_s)$

   ➔ Enables us to obtain the (pseudo-)rapidity dependence of observable.

      ➔➔ $v_2(\eta)$, $R_i(Y)$ (i=out, side, long), etc.

➢Not the Cartesian coordinate, but the τ-η_s coordinate

   ➔ It is relevant to the collider energies.

      ➔➔ Observables at RHIC

$$\tau = \sqrt{t^2 - z^2} \, , \eta_s = \frac{1}{2} \ln \frac{t+z}{t-z}$$

Early Chemical Freeze Out

In the conventional hydrodynamics, one assumes

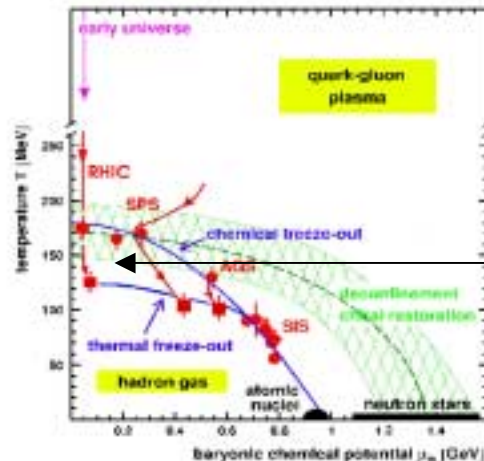$$T_{\text{chemical f.o.}} = T_{\text{thermal f.o.}}$$

Figure from
U. Heinz, hep-ph/0109006.

motivation

Chemically frozen but thermally equilibrated

"*Early*" means that chemical freeze out in our model happens earlier than in the conventional one. So, in our hydro model,

$$T_{\text{chemical f.o.}} > T_{\text{thermal f.o.}}$$

(Approximation $\mu_B = 0$ for the RHIC energy)

See, for example, T.Hirano and K.Tsuda, nucl-th/0205043; D.Teaney, nucl-th/0204023.

Model EOS

- ➢ QGP phase (massless free u, d, s and g : $P=(E-4B)/3$)
- ➢ Mixed phase ($T_c=$170 MeV)
- ➢ Hadron Phase (All hadrons up to $\Delta(1232)$.)
  - ✧ Model 1 Chemical Equilibrium (CE)
  - ✧ Model 2 Chemical Freeze-Out (CFO)
  - ✧ Model 3* Partial Chemical Equilibrium (PCE)

Temp. (MeV)	Model 1 (CE)	Model 2 (CFO)	Model 3* (PCE)
170 ($=T_{ch}$)	π ρ	π ρ	π ρ ρ
140 ($=T_{th}$)	π ρ	π ρ	π ρ ρ $\pi\pi \to \rho \to \pi\pi$
Conserved quantities	S	S, N_π, N_ρ	$S, \overline{N_\pi}=N_\pi+2N_\rho$

Equation of State

- Approximation $\mu_B = 0$ for the RHIC energy

PRESSURE:
Three models are very similar to each other.

TEMPERATURE:
- At a fixed T, E in PCE and CFO are larger than in CE due to large fraction of resonances.
- PCE looks like CFO rather than CE.

Time Evolution of *E* and *T*
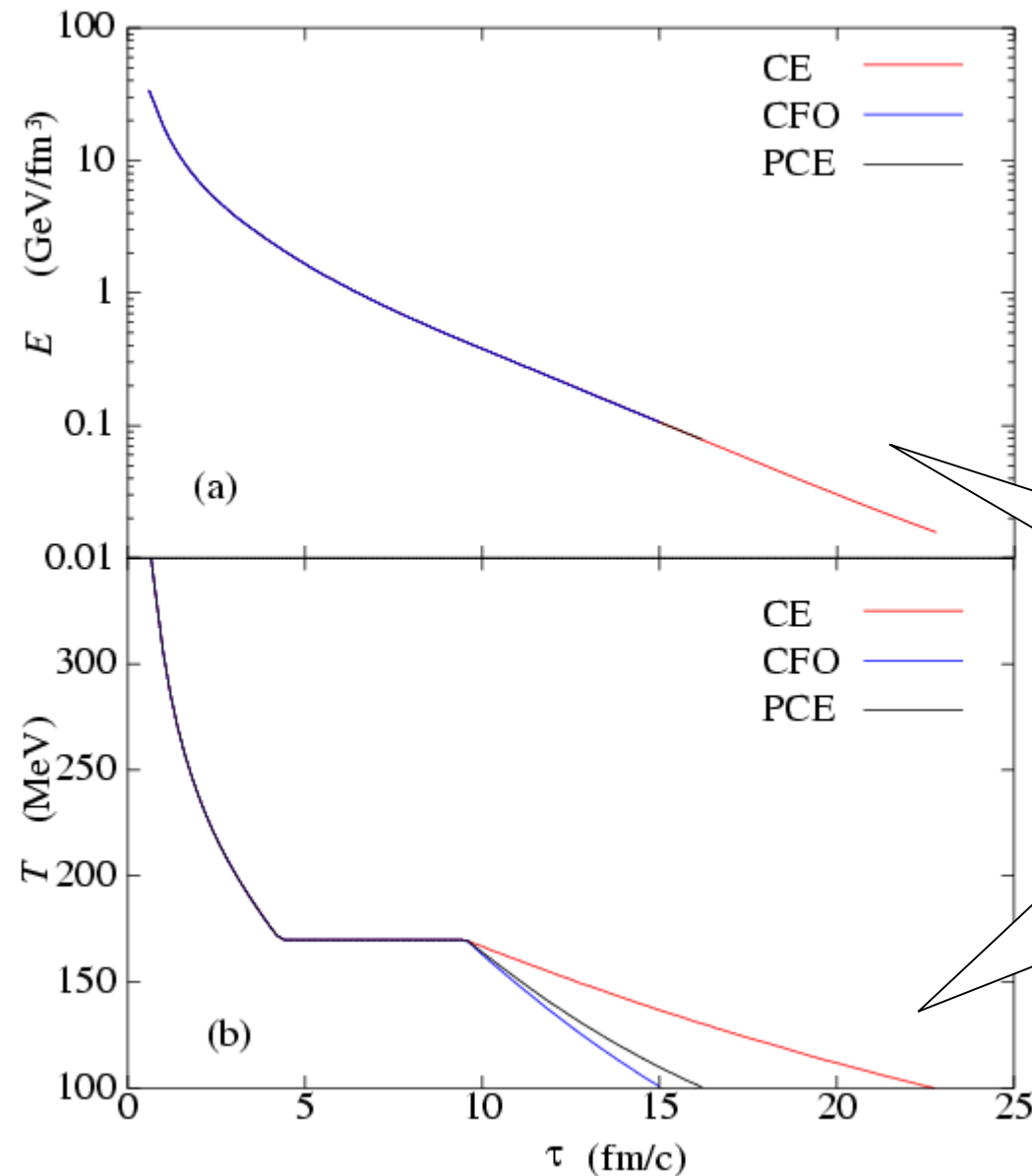
Initial condition in central collisions at the RHIC energy:
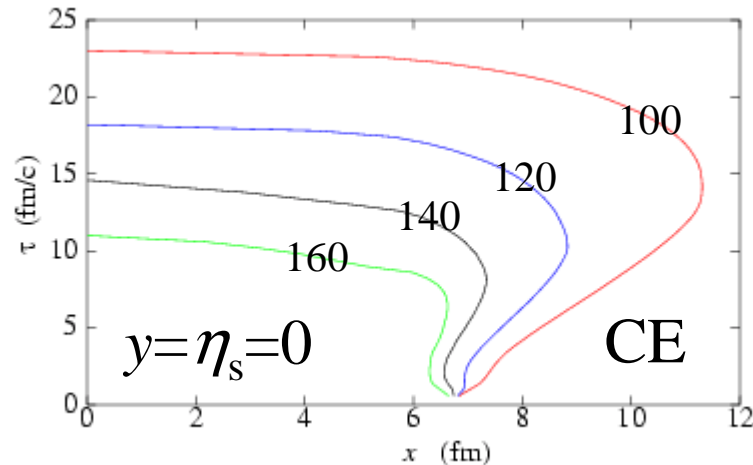
$\tau_0 = 0.6$ fm
$b = 2.4$ fm
$E(\tau_0, \mathbf{0}) = 33.7$ GeV/fm^3
$T(\tau_0, \mathbf{0}) = 357.5$ MeV

Energy density: Not distinguishable

Chemical freeze-out makes the hadron phase cool down more rapidly !

Time Evolution of Hypersurface

Chemical Equilibrium model
- Explosive expansion in the hadron phase
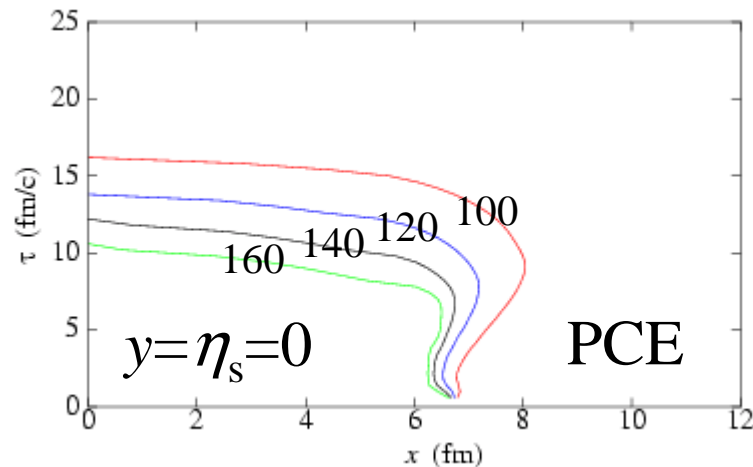
Partial Chemical Equilibrium
- Expansion is not so explosively due to early chemical freeze out.

Effects on HBT Radii ? → I′ll show you later.

T^{th} vs. $<v_r>$ at $\eta_s=0$

CE: Chemical Equilibrium
CFO: Chemical Freeze-Out
PCE: Partial Chemical Equilibrium
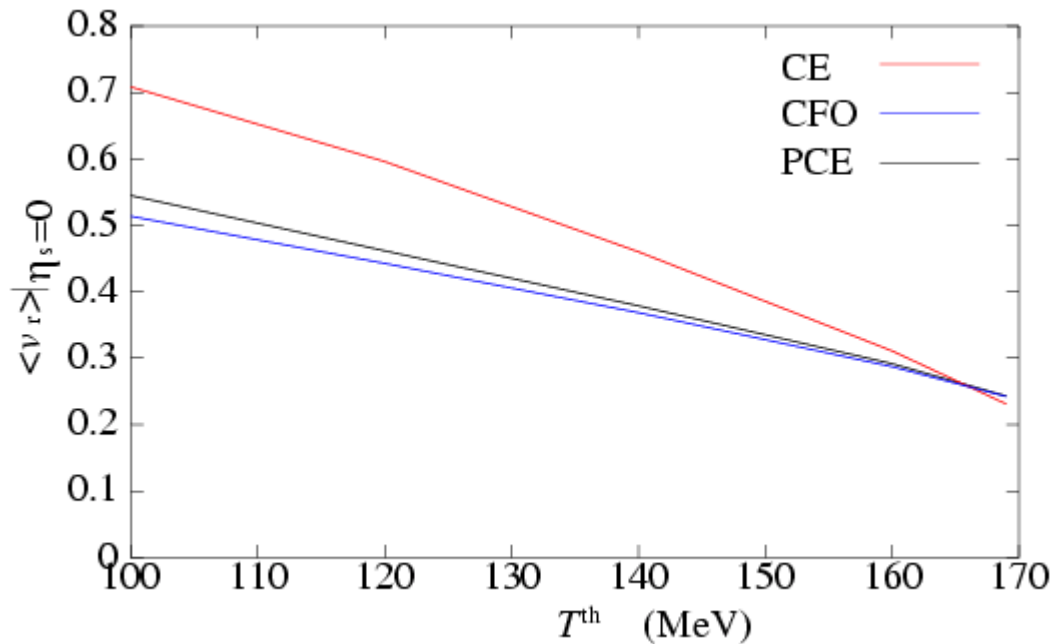
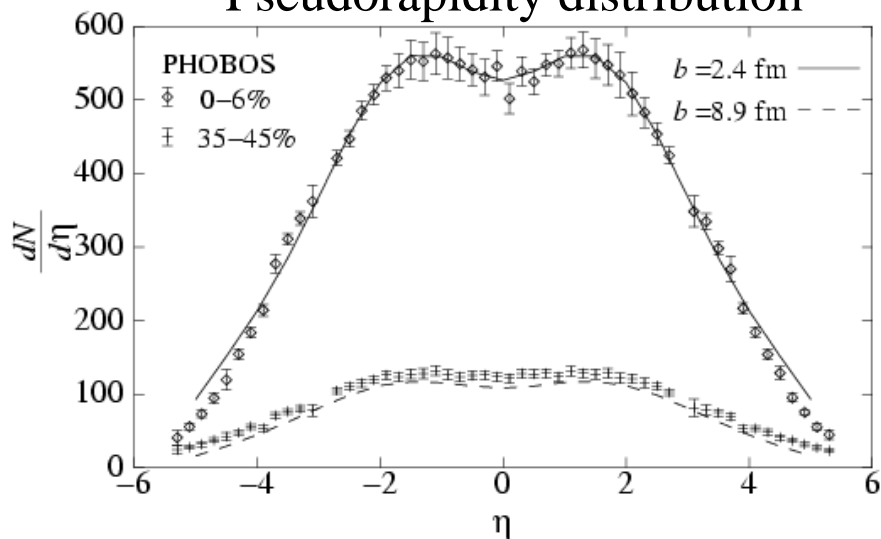$\langle\cdots\rangle$: average over thermal
freeze out hypersurface

Suppression of $<v_r>$:
17.7 % (T^{th}=140 MeV)
22.5 % (T^{th}=120 MeV)

Radial flow is suppressed.
Chemical freeze-out affects the p_t slope.

Single Particle Distribution of Charged Particles in Au+Au 130A GeV Collisions

Model PCE

Pseudorapidity distribution

T^{th}=140 MeV
Binary collision scaling

Data from PHOBOS (QM2001)

Transverse momentum spectra
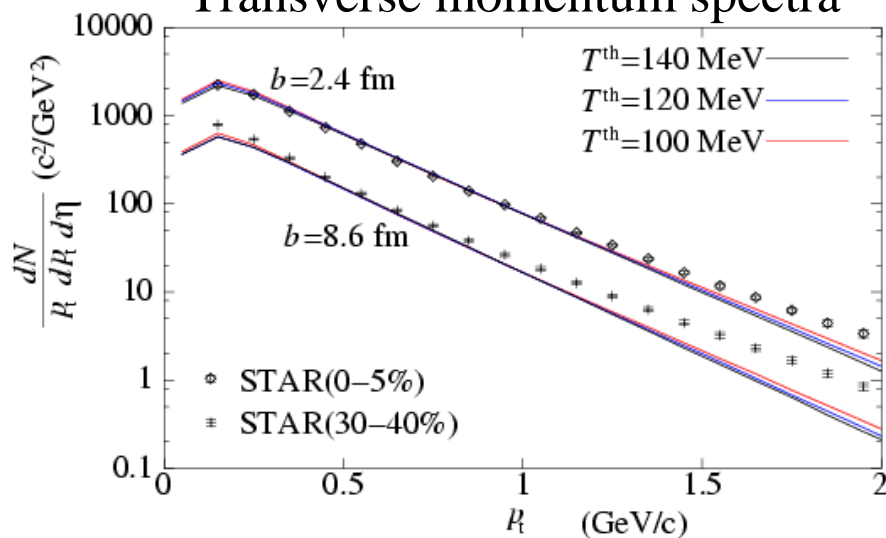
Almost T^{th} independent !
←Due to suppression of transverse flow in the model PCE

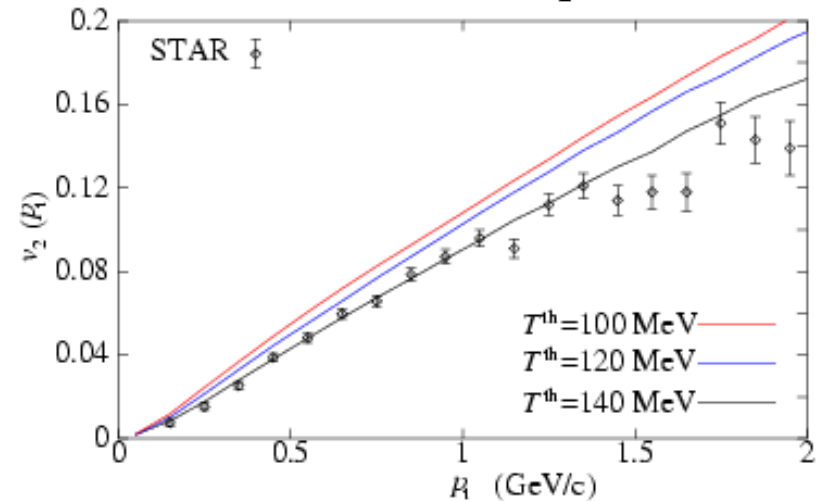Data from STAR, PRL87, 112303 (2001);nucl-ex/0111004.

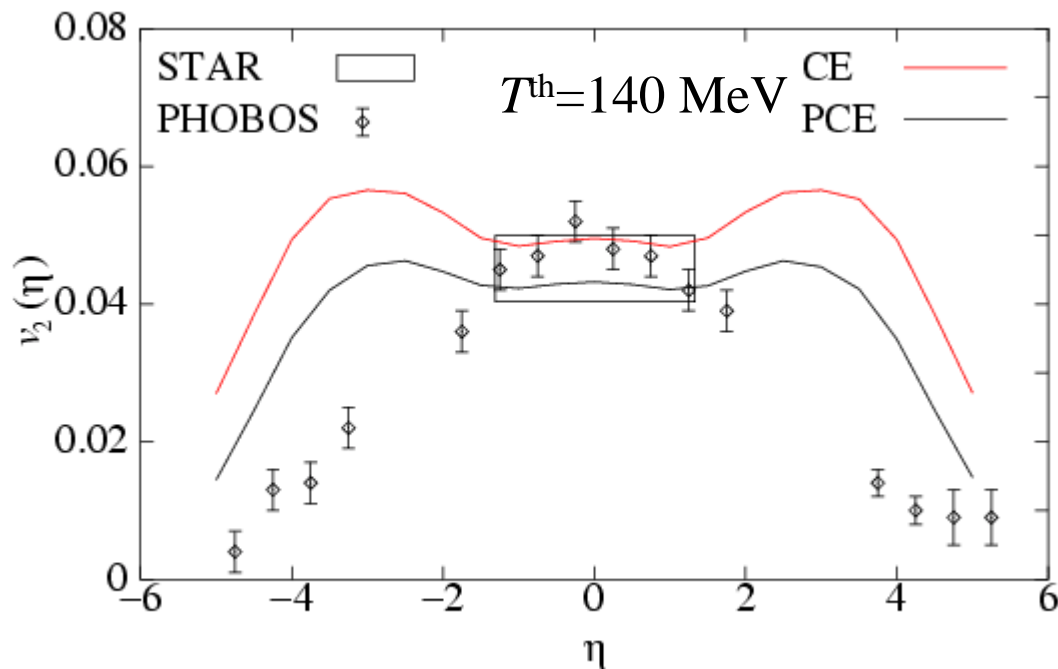# $v_2(p_t)$ for Charged Hadrons

Chemical Equilibrium
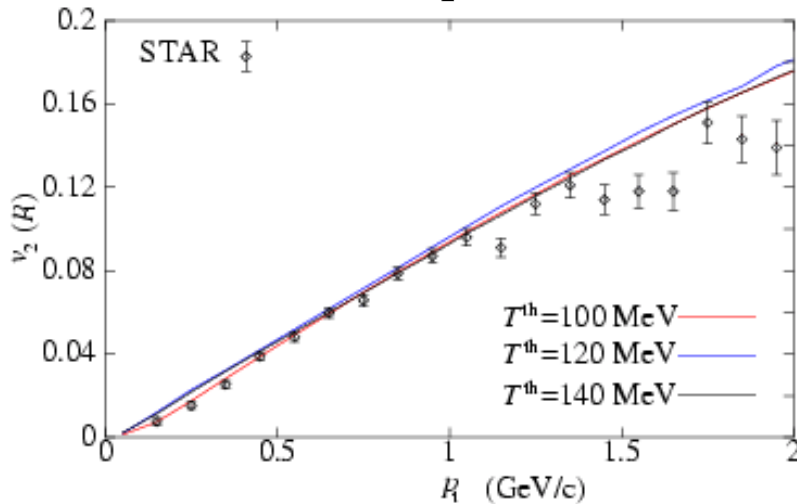
Partial Chemical Equilibrium

Almost T^{th} independent

v_2 depends on T^{th}
in the model PCE !
T^{th}=140 MeV ?

Data from STAR, PRL86,402(2001).

$v_2(\eta)$ for Charged Hadrons

Our results:
   $0<p_t<2$ GeV/c
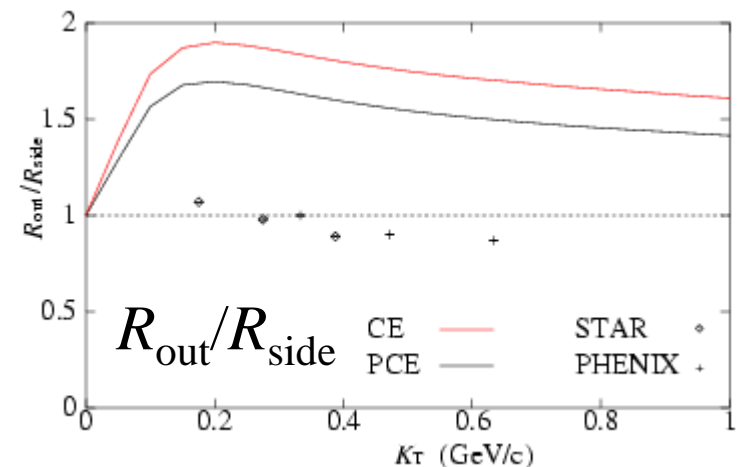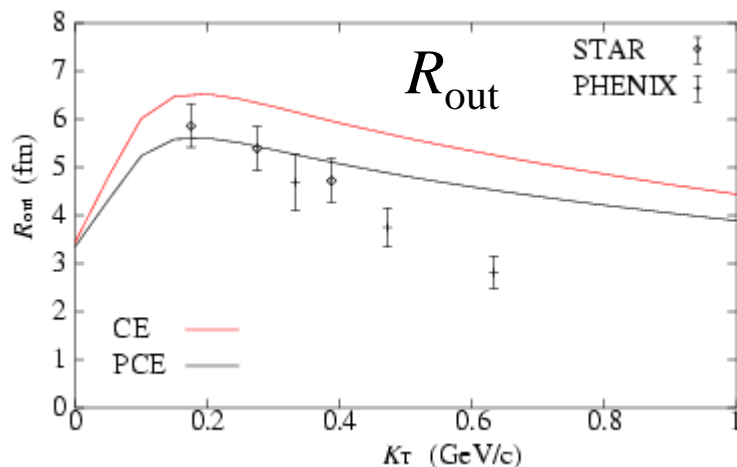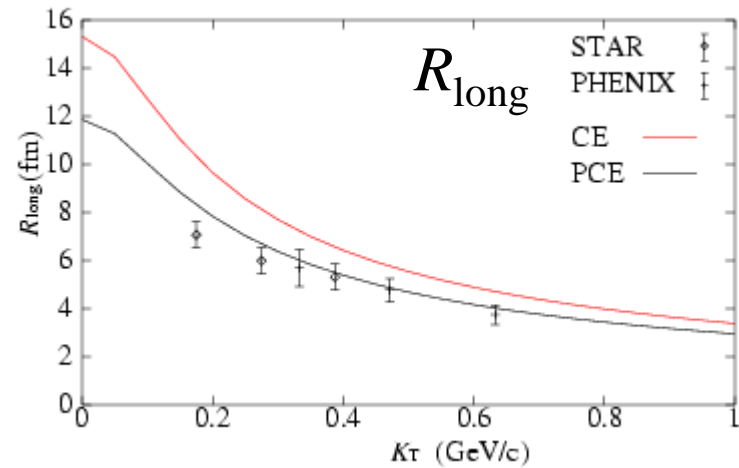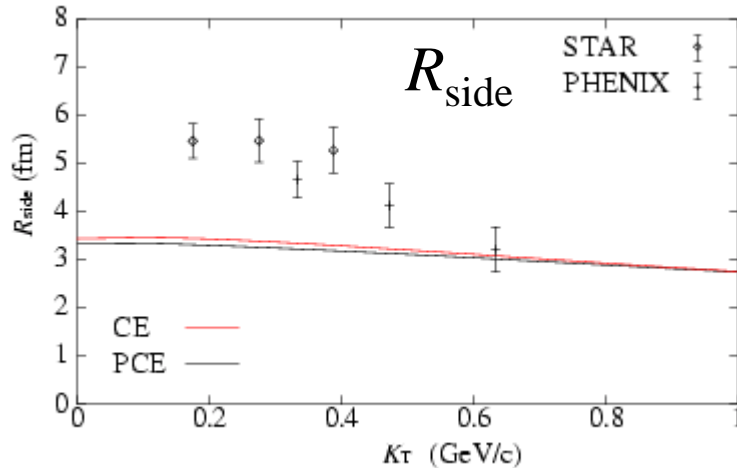PHOBOS:
   All p_t
STAR:
   $0.1<p_t<2$ GeV/c

Elliptic flow is also suppressed !

Note: v_2 in forward and backward region is sensitive
to the initial shape of energy density. → Detailed analyses are needed !

Data from PHOBOS, (QM2001); STAR, PRL86,402(2001).

K_T dependence of HBT Radii

• T^{th}=140 MeV, negative pions, neglecting resonance decays.

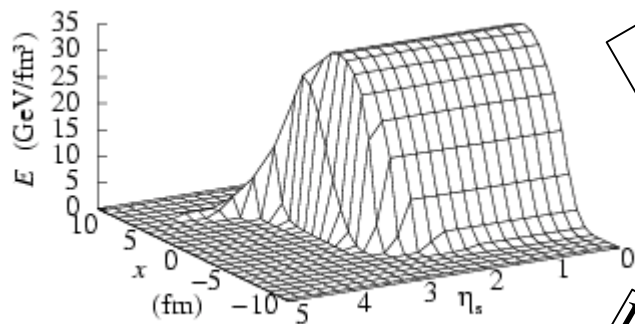Data from STAR, PRL87, 082301 (2001), PHENIX, PRL88, 192302 (2002).

Summary

- Fully 3D hydrodynamic simulations at the RHIC energy by using EOS with/without chemical equilibrium
- In comparison with the model CE, the model PCE shows that
  - radial flow is suppressed.
  - temporal/spatial size of the fluid is reduced.
  - elliptic flow is also suppressed and the resultant v_2 depends on T^{th}.
  - HBT radii are also reduced.
- Nevertheless, it is not enough to completely interpret the HBT puzzle.

Anyway, one should really include the properties of chemical freeze out in hydrodynamic simulations !

Initial Condition of Energy Density

Initial energy density
in the reaction plane

Binary collision scaling:
$$W = \alpha\, T(x+b/2,y)T(x-b/2,y)$$

transverse

$$E(x, y, \eta_s; b) = E_{max} W(x, y; b) H(\eta_s)$$

longitudinal

Parameters for central collisions:
$b = 2.4$ fm
$\tau_0 = 0.6$ fm
$E_{max} = 35$ GeV/fm^3
$\eta_{flat} = 5.8$
$\eta_{Gauss} = 0.2$
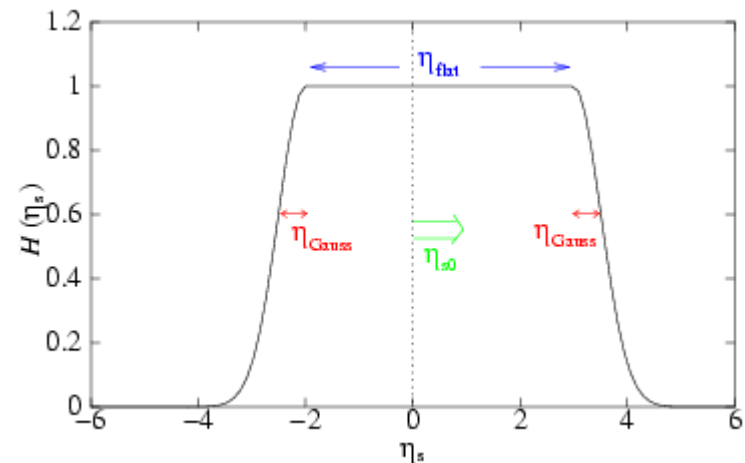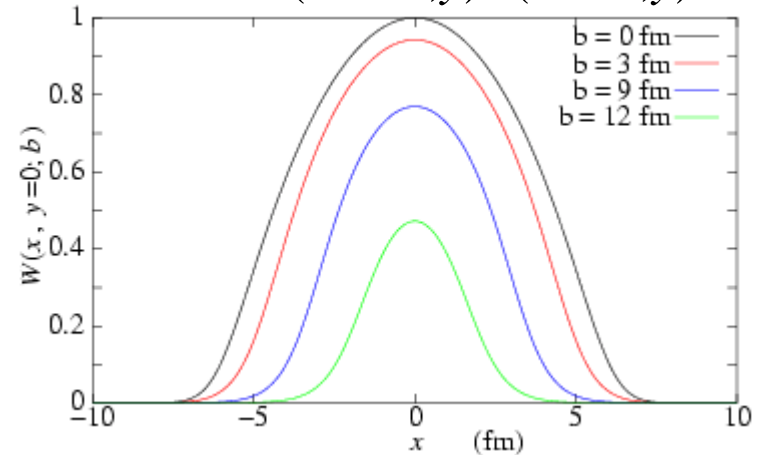
Local Rapidity Shift

Global center of rapidity = 0
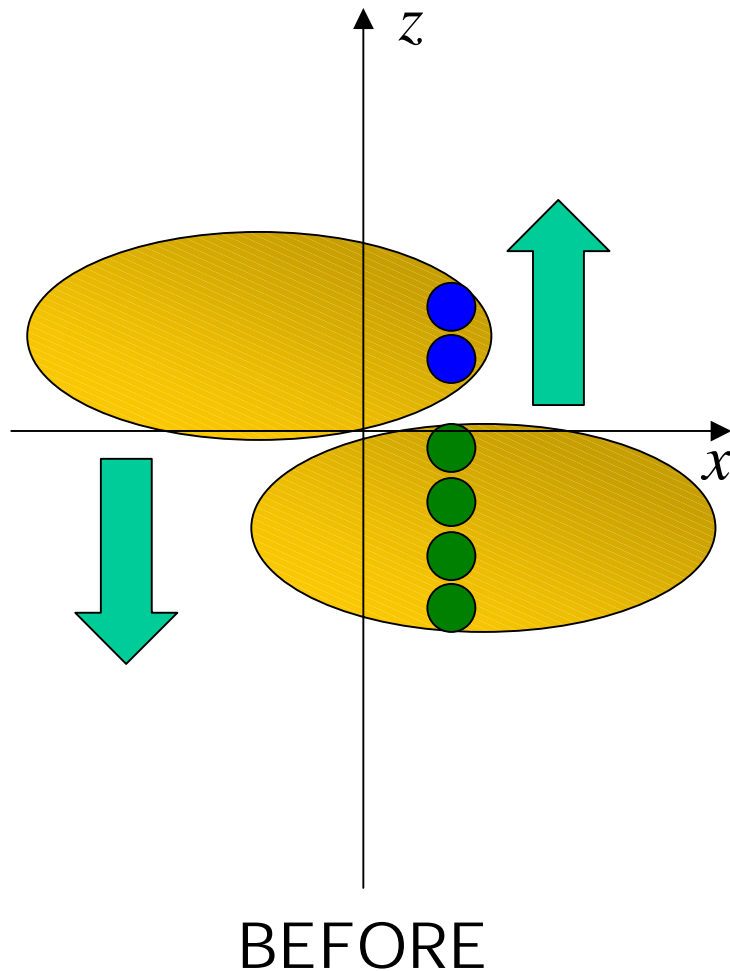
$\eta_{s0}(x<0)<0$

Local rapidity shift

$\eta_{s0}(x>0)>0$

BEFORE

AFTER
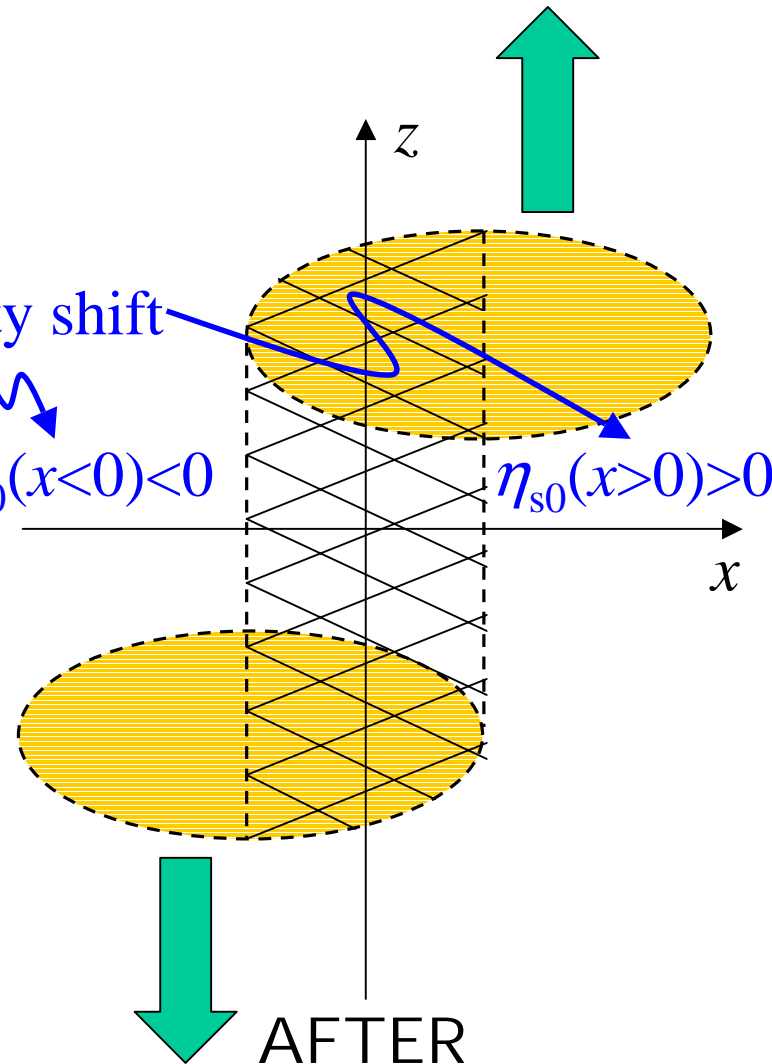
p_t Spectra for Identified Particles

Chemical Equilibrium

Partial Chemical Equilibrium
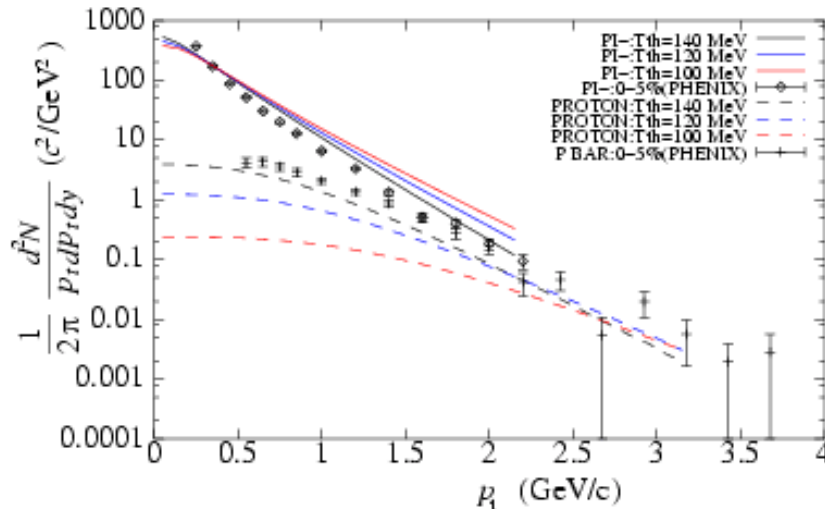
The p_t slope depends on T^{th} in the conventional model EOS.
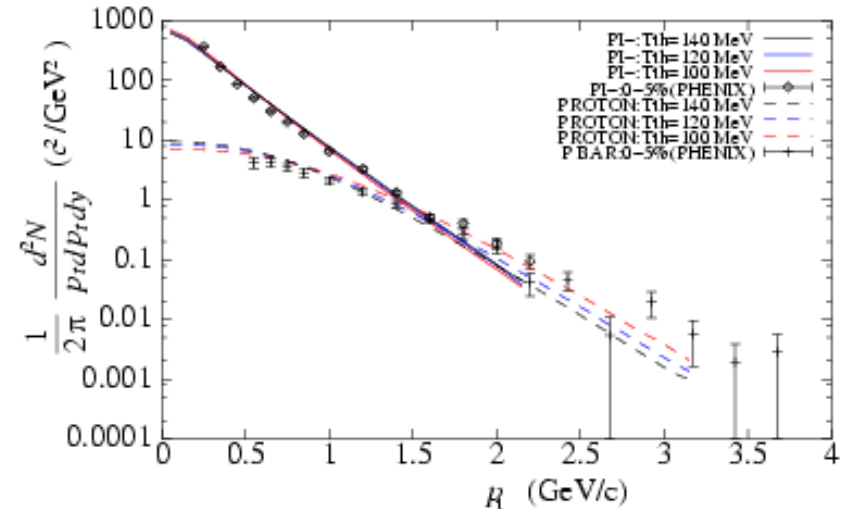
The slopes of π are almost independent of Tth.

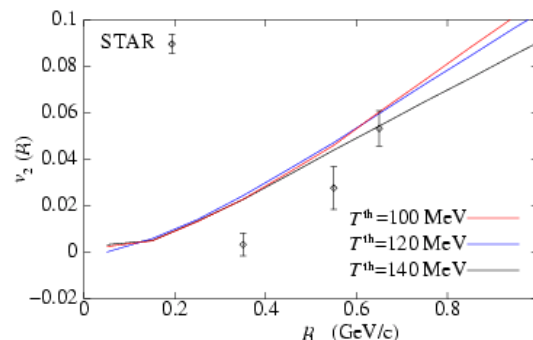Data from PHENIX, nucl-ex/0112006.
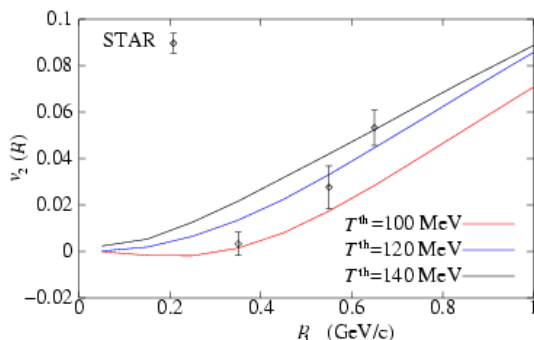
$v_2(p_t)$ for Pions, Kaons and Protons
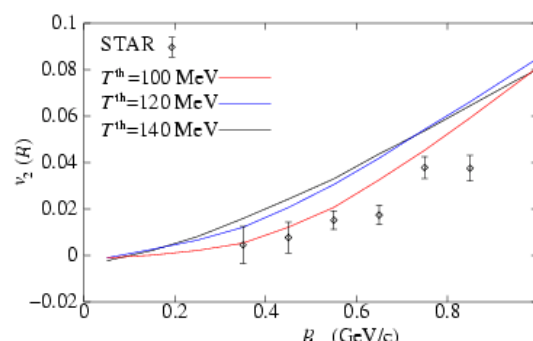
Chemical Equilibrium

Partial Chemical Equilibrium

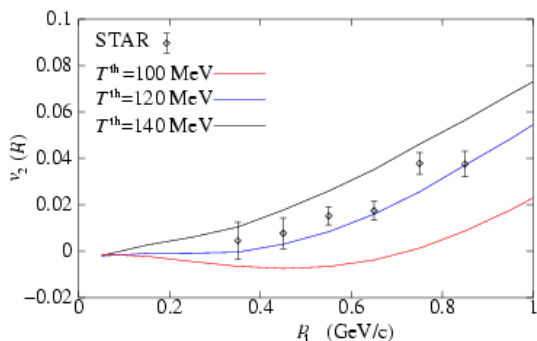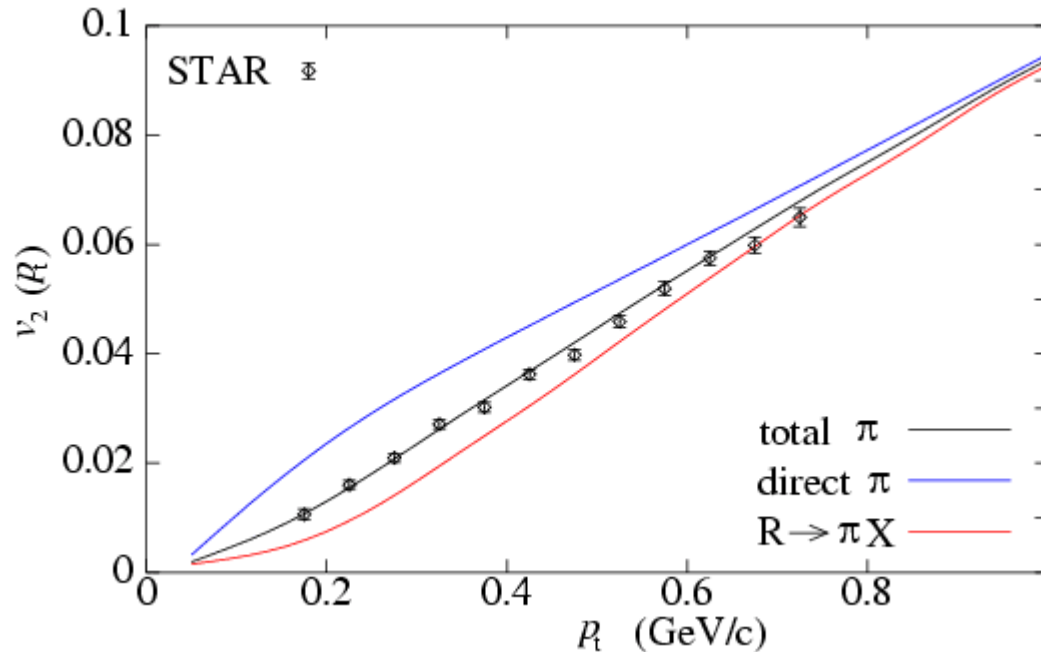π
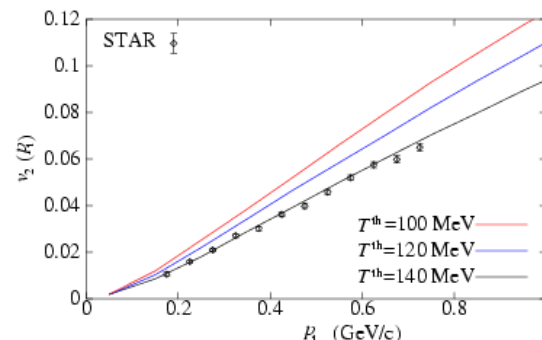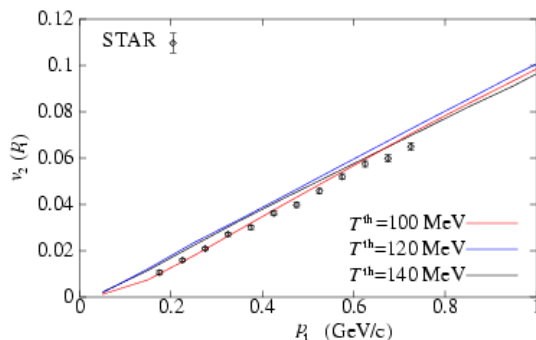
K

p

$v_2(p_t)$ for direct and indirect pions

Resonance decays
dilute elliptic flow
from direct pions.
➔For its mechanism, see,
 T.Hirano,PRL**86**,2754(2001).

Population of resonances is very important
in low pt region !
➔ Need to include early chemical freeze out.

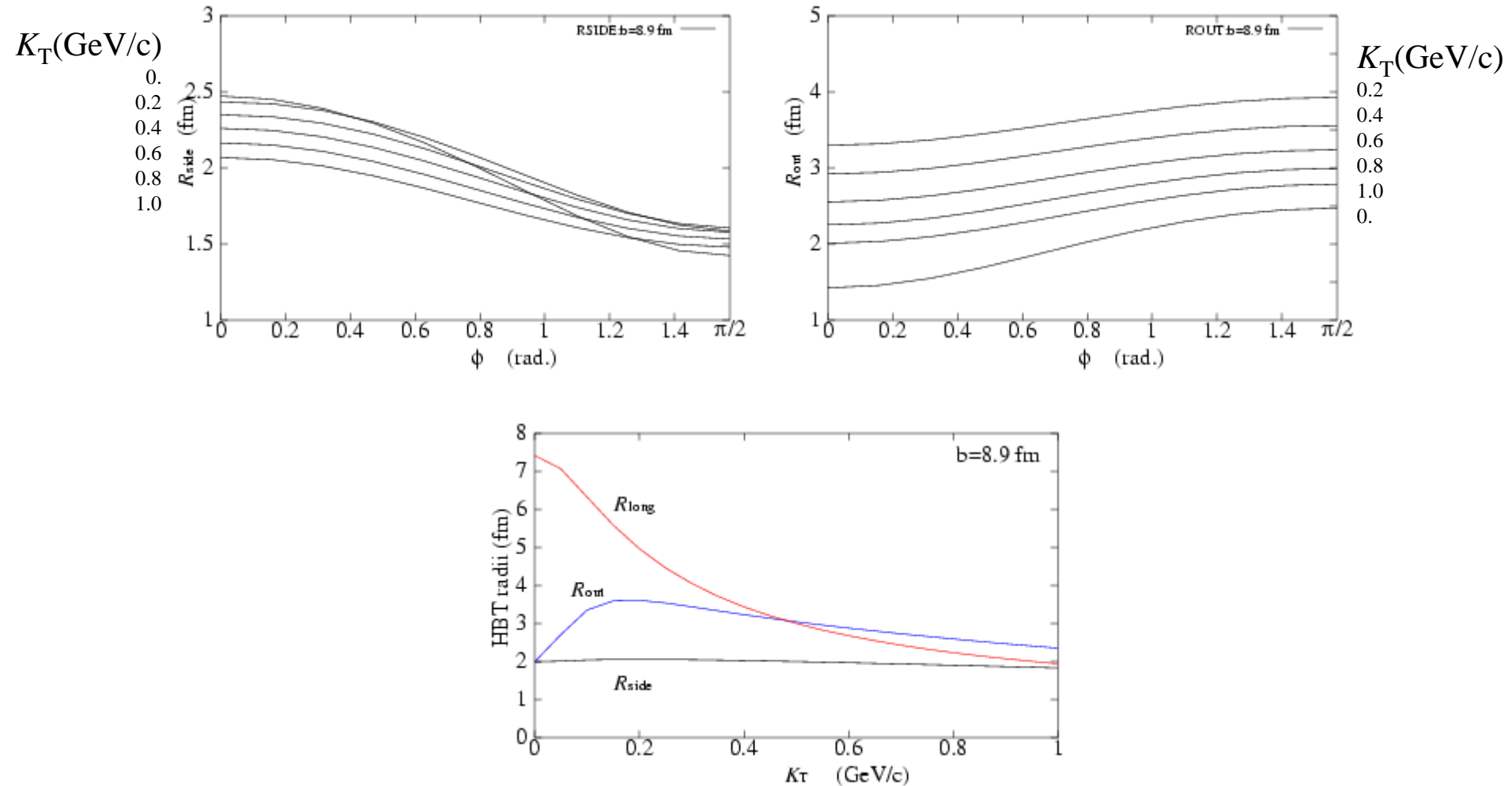# Variance of Initial Energy Density in the Transverse Plane

$$\langle R \rangle = \frac{\int dxdy \sqrt{x^2 + y^2} E(\tau_0, \eta_s = 0, x, y)}{\int dxdy E(\tau_0, \eta_s = 0, x, y)}$$

For nuclear density, the standard Woods-Saxon parameterization with $R_0 = 1.12 A^{1/3} - 0.86 A^{-1/3}, A = 197, \delta = 0.54$fm
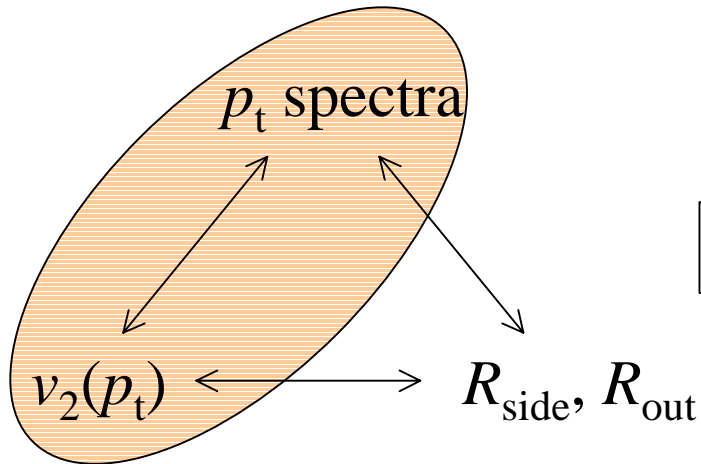
Results (fm):
- 3.26 (binary collision scaling, b=2.4 fm)
- 3.40 (binary collision scaling, b=0 fm)
- 3.74 (wounded nucleon model, b=2.4 fm)
- 3.88 (wounded nucleon model, b=0 fm)
- 4.44 (prop. to Woods-Saxon)
- 5.78 (flat + Gauss)

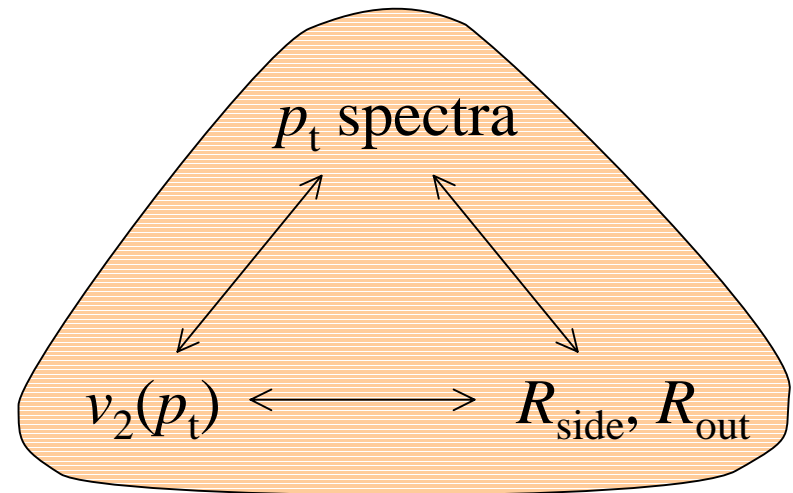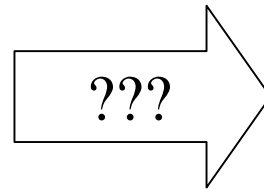# HBT Radii in Non-Central Collisions

Discussion

- Transverse dynamics

p_t spectra

$v_2(p_t)$ $\longleftrightarrow$ R_{side}, R_{out}

???

p_t spectra

$v_2(p_t)$ $\longleftrightarrow$ R_{side}, R_{out}

present initial condition

future !?

Are there any initial conditions compatible with all three observables ?